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Late Quaternary glaciation in the Tianshan and implications for palaeoclimatic change: a review

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The Tianshan mountain range has been extensively and repeatedly glaciated during the late Quaternary. Multiple moraines in this region record the extent and timing of late Quaternary glacier fluctuations. The moraines and their ages are described in three sub-regions: eastern, central and western Tianshan. Notable glacial advances occurred during marine oxygen isotope stages (MIS) 6, 4, 3, 2, the Neoglacial and the Little Ice Age (LIA) in these sub-regions. Glaciers in western Tianshan advanced significantly also during MIS 5, but not in eastern and central Tianshan. The local last glacial maximum (llgm) of the three sub-regions pre-dated the Last Glacial Maximum (LGM) and occurred during MIS 4 in eastern and central Tianshan, but during MIS 3 in western Tianshan. The spatial and temporal distribution of the glaciers suggests that precipitation (as snow at high altitude) is the main factor controlling glacial advance in the Tianshan. The late Quaternary climate in the Tianshan has been generally cold–dry during glacial times and warm–humid during interglacial times. Between neighbouring glacial times, the climate has had a more arid tendency in eastern and central Tianshan. These palaeoclimatic conditions inferred from glacial landforms indicate important relationships between the mid-latitude westerly, the Siberian High and the Asian monsoon.

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Mountain glaciers are sensitive indicators of regional and local climate, and thus records of past glacial advances preserved in moraines, glacial extent and other geomorphic features are valuable clues of past climatic change, especially if the chronology of the glaciations is constructed accurately (Thackray *et al*. 2008). In southern parts of Central Asia, mountain glaciation is largely controlled by the Asian monsoon (Indian monsoon and Southeast Asian monsoon) and the mid-latitude westerly (Shi 2002; Cui & Zhang 2003; Owen *et al*. 2005). However, owing to its special location north towards the Tibetan Plateau, and being the boundary between the westerly circulation and the Asian monsoon, the Tianshan mountain range has been governed, alternately or in combination with: the mid-latitude westerly originating from the North Atlantic and the Mediterranean, the Siberian High and the changeable but much weaker Asian monsoon (Shi *et al*. 1994; Rhodes *et al*. 1996; Tarasov & Harrison 1998; Liu *et al*. 2008). Figure 1 shows the present influential area of these three climatic systems in Central Asia. However, the correlation between them is poorly understood, especially during glacial times, and therefore studying the glaciation in the Tianshan can help to better quantify the evolution of these climatic systems.

Until the advent of numerical dating techniques towards the end of the last century, alpine glacier advance in Central Asia was considered to be synchronous with expansion of the high-latitude ice sheets, especially to the Last Glacial Maximum (LGM) (Anderson & Prell 1993; Emeis *et al*. 1995; Kuhle 1998). This was because researchers, owing to lack of knowledge of the ages of moraines, considered prominent moraines to have formed during the LGM, or perhaps it was a coincidence that mountain glaciers synchronously advanced with ice-sheet expansion during the LGM. Strictly speaking, the LGM is defined chronologically based on ages 19–23 kyr (Chronozone level 1) or 18–24 kyr (Chronozone level 2) within MIS 2 (Mix *et al*. 2001). As refined numerical dating methods, such as optical stimulating luminescence (OSL), electron spin resonance (ESR) and cosmogenic radionuclide (CRN), have become more widely used, new studies have shown that Asian glaciers reached their maximum extents at different times compared to the ice sheets of Europe and North America (Gillespie & Molnar 1995; Shi 2002; Zhang *et al*. 2006). Even within Asia, it has been known that there is regional variability in the timing of glacial fluctuations (Gillespie & Molnar 1995; Benn & Owen 1998; Shi 2002; Finkel *et al*. 2003; Owen *et al*. 2003a, 2005, 2006). Moreover, increasing glacial chronologies in Asian mountains present a similar trend as major glacier advances during the late Quaternary, becoming progressively less extensive with time (Benn & Owen 1998; Zheng *et al*. 2002; Owen *et al*. 2005; Owen 2008, 2009).

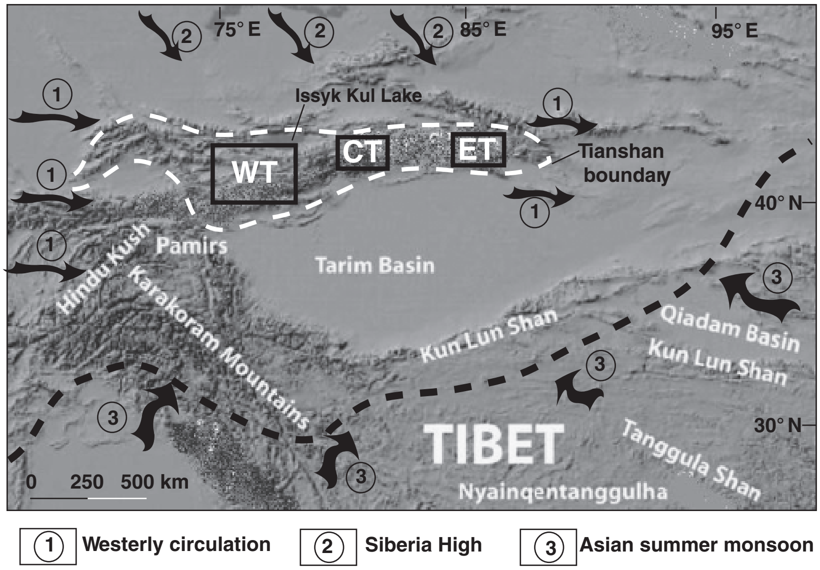

Fig. 1. Position of the Tianshan mountain range in Central Asia and climatic systems in this region. The area enclosed by the dashed white line is the Tianshan, while the black rectangles show the three sub-regions: eastern Tianshan (ET, more details in Figs 2, 3), central Tianshan (CT, more details in Fig. 4) and western Tianshan (WT, more details in Figs 5–7). The dashed black line indicates the present northern limit of Asian monsoon precipitation (after Shi 2002). The black arrows show the directions of the climatic systems (after Lehmkuhl & Haselein 2000; Zhang *et al.* 2000; Yang *et al.* 2004; Owen *et al.* 2005).

Recently, numerical dating technologies have sparked renewed interest in the Tianshan, providing new insights into the nature of Late Pleistocene and Holocene glacial fluctuations and thereby offering the possibility to test the asynchronous feature of glacial advance. Also, a clear understanding of these glacial fluctuations, combined with other climatic proxies, may help us recognize the evolution of arid and semi-arid environments in Central Asia. This article focuses on the glaciation in the Tianshan and its implications for the palaeoclimate. For comparison with the commonly used 'LGM', the Tianshan maximal glacial during the Last Glacial is named 'local last glacial maximum (llgm)'.

Regional setting

The Tianshan mountain range, as large as but not higher than the Himalaya, essentially results from the collision of the Indian and Eurasian continental plates (Yin & Harrison 2000; Thompson *et al.* 2002) and comprises many individual ranges. These ranges are tectonically active and stretch ~2500 km in a SW–NE arc from the western boundary of Kyrgyzstan through Xinjiang (China), almost as far east as to Mongolia. The mountain system has an average altitude of ~4000 m above sea level (a.s.l.); the highest peak is Tumur (7435.3 m a.s.l.), which is the centre of modern glaciers in the central Tianshan.

Precipitation in the Tianshan is mainly from the moisture carried by the westerly, and low temperature is due to the Siberian High. In winter, the Siberian High strongly affects this area, but in spring the weakened Siberian High allows the invasion of moisture by the westerly to the inner Tianshan, so the maximum precipitation is observed in spring/summer (Aizen *et al.* 1995). The annual precipitation varies from 200–450 mm in the east to 300–1000 mm in the west, and the annual average temperature varies between 2.1 °C (~2000 m a.s.l.) and −7.1 °C (~4000 m a.s.l.) (Li 2006). According to Derbyshire *et al.* (1991) and Shi (2002), the glacial regime in the Tianshan is a continental type.

Material and methods

Many of the palaeoclimatic conclusions that we derive from this review are based on glaciation and its timing. Therefore, in compiling and assessing recent studies, we review the current knowledge of the extent and timing of the late Quaternary glaciation of the Tianshan. The Tianshan is divided into three regions: eastern, central and western. The first two are situated in Xinjiang, NW of China, while the third is in Kyrgyzstan (Fig. 1). To systematically investigate the glacial landforms in the Urumqi River Valley in eastern Tianshan, we undertook fieldwork in 2008 and specifically measured end and/or lateral moraine elevations of each glaciation using handy GPS (global positioning). Based on our fieldwork and recent published studies, we summarize the glacial extents in different glaciations for the three regions of the Tianshan. To maintain consistency, the glacial extents in the three regions are described from young to old in this article. All the dating results for the glaciations are reviewed from published studies and are listed in Table 1. The ages, with the exception of radiocarbon ages, are directly cited from the published studies. To allow comparisons to be made between the ESR, OSL and CNR ages, in this article the radiocarbon ages have been calibrated using the software CALIB Rev 5.0 of Reimer *et al.* (2004) and presented in 'cal. kyr BP'.

Table 1. Absolute ages of the late Quaternary glacial extents of Tianshan.

Valley	Location (°N, °E)	Elevation (average m a.s.l.)	Name of moraine set	Dating method	Dating result	Glacial stage	Source
Urumqi River	43.11 86.81	3670	First set	Lichenology	AD 1538±20, AD 1777±20, AD 1871±20	Little Ice Age	Chen (1989)
				AMS ^{14}C	430, 390 cal. yr BP		Yi *et al.* (2004)
	43.10 86.82	3540	Second set	AMS ^{14}C	1.79 cal. kyr BP (outer layer of coating), 7.46 cal. kyr BP (inner layer of coating)	Neoglacial	Yi *et al.* (2004)
				^{14}C	4.38, 4.59, 6.49 cal. kyr BP		Zheng & Zhang (1983)
	43.11 86.83	3250	Shangwangfeng	^{14}C	17.89, 10.38 cal. kyr BP (loess cover)	MIS 2–3	Wang (1981)
				AMS ^{14}C	23080±510 a BP*, 22.66 cal. kyr BP		Yi *et al.* (2004)
				ESR	37.4#, 27.6#, 35±3.5 kyr BP		Yi *et al.* (2001); Zhao *et al.* (2006)
	43.11 86.84	2940	Xiawangfeng	TL	37.7±2.6 kyr BP (fluvial sand at the bottom of the till)	MIS 3	Li (1995)
				ESR	72.6#, 58.6#, 56.6#, 54.6#, 40.1 kyr BP# (fluvial sand)	MIS 4	Yi *et al.* (2001)
				ESR	184.7±18, 176±18, 171.1±17 kyr BP	MIS 6	Zhao *et al.* (2006)
	43.10 86.83	3450	Gaowangfeng	ESR	477.1, 459.7±46 kyr BP	MIS 12	Zhou *et al.* (2001); Zhao *et al.* (2006)
Ateaoyinake River	41.71 80.23	3034	Second set	ESR	3.4±0.4, 6.8±0.6 (bottom outwash sand), 7.3±0.8 kyr BP (bottom outwash sand)	Neoglacial	Zhao *et al.* (2009)
	41.70 80.24	3063	Third set	OSL	12.3±1.2 kyr BP	MIS 2	—
				ESR	14.3±1.3, 18.1±1.8, 17.4±1.6, 21.1±2.1, 26.7±2.5 kyr BP		—
	41.69 80.23	3074	Fourth set	ESR	40.9±4.0, 46.2±4.2, 51.0±4.8, 54.0±5.2 kyr BP	MIS 3	—
	41.67 80.25	3031	Fifth set	ESR	55.4±5.2, 60.2±5.7, 62.3±5.8 kyr BP	MIS 4	—
	41.66 80.23	2980	Sixth set	ESR	134.4±12.6, 219.7±20.5 kyr BP	MIS 6	—
	41.71 80.23	3327	Qingtoushan	ESR	440.6±41.7 kyr BP	MIS 12	—
Gulbel	42.03 77.19	3283	Unit 4	CRN	32.4±2.4–59.2±5.1, 40.5±3.1–76.8±6.9 kyr BP	MIS 3	Koppes *et al.* (2008)
	42.04 77.21	3140	Unit 5	CRN	30.0±2.3–49.3±4.1, 41.9±3.3–72.0±6.6 kyr BP	MIS 3	—
	42.04 77.12	2759	Unit 5	CRN	98.1±7.9–155.1±15.1 kyr BP	MIS 6- early MIS 5	—
Ala Bash	42.05 76.43	3750	Unit 1	CRN	3.4±0.3–3.4±0.3 kyr BP	Neoglacial	—
	42.05 76.43	3750	Unit 2	CRN	17.8±1.3–18.3±1.4 kyr BP	MIS 2	—
	42.08 76.46	2496	Unit 3	CRN	64.0±4.8–72.5±6.2, 69.9±5.3–80.3±7.1 kyr BP	Late MIS 5-MIS 4	—

	42.05 76.43	2850	Unit 4	CRN	50.1±3.8–55.1±4.6, 93.0±7.4–113.4±11.4 kyr BP	MIS3/MIS 5	—
	42.08 76.46	2403	Unit 5	CRN	134.6±12.7–187.9±26.8, 163.5±14.1–259.6±41.7 kyr BP	MIS 6	—
	42.08 76.45	2229	Unit 5	CRN	97.7±8.0–120.8±12.6, 108.4±9.0–138.3±15.3 kyr BP	MIS 5	—
Aksai	41.00 76.05	3879	Unit 1	CRN	4.4±0.3–4.5±0.3, 4.6±0.3–4.7±0.4 kyr BP	Neoglacial	—
	41.00 76.10	3804	Unit 2	CRN	7.4±0.6–7.6±0.6 kyr BP	Neoglacial	—
	40.98 76.15	3576	Unit 3	CRN	36.5±2.7–39.0±3.1 kyr BP	MIS 3	—
At Bashi	41.05 75.73	2598	Unit 3	CRN	31.6±2.4–33.5±2.7 kyr BP	Late MIS 3	—
	41.05 75.73	2598	Unit 4	CRN	52.5±4.0–58.0±5.0 kyr BP	Early MIS 3	—
Ala Archa	42.52 74.51	3246	Unit 1	CRN	0.24±0.1–0.25±0.1 kyr BP	Little Ice Age	—
	42.52 74.51	3180	Unit 2	CRN	0.54±0.1–0.54±0.1 kyr BP	Little Ice Age	—
Temir-Kyrnat				OSL	56.3±5.8 kyr BP	Early MIS 3	Narama *et al.* (2009)
				OSL	71.3±5.6 kyr BP	MIS 4	—
Terek-Suu				OSL	33.4±2.7 kyr BP	Late MIS 3	—
Taldy-suu				OSL	26.3±2.2 kyr BP	MIS 2	—
Chon-Tor				OSL	17.9±1.4 kyr BP	MIS 2	Narama *et al.* (2007)
Sary-Tal				OSL	24.3±1.9 kyr BP	MIS2	—
				OSL	31.5±2.7 kyr BP	Late MIS 3	—

*AMS ^{14}C not calibrated due to the age over the upper limit (21 381 years) of Reimer *et al.* (2004).
#The ESR age not given any uncertainty.
— The same reference as the one immediately above.

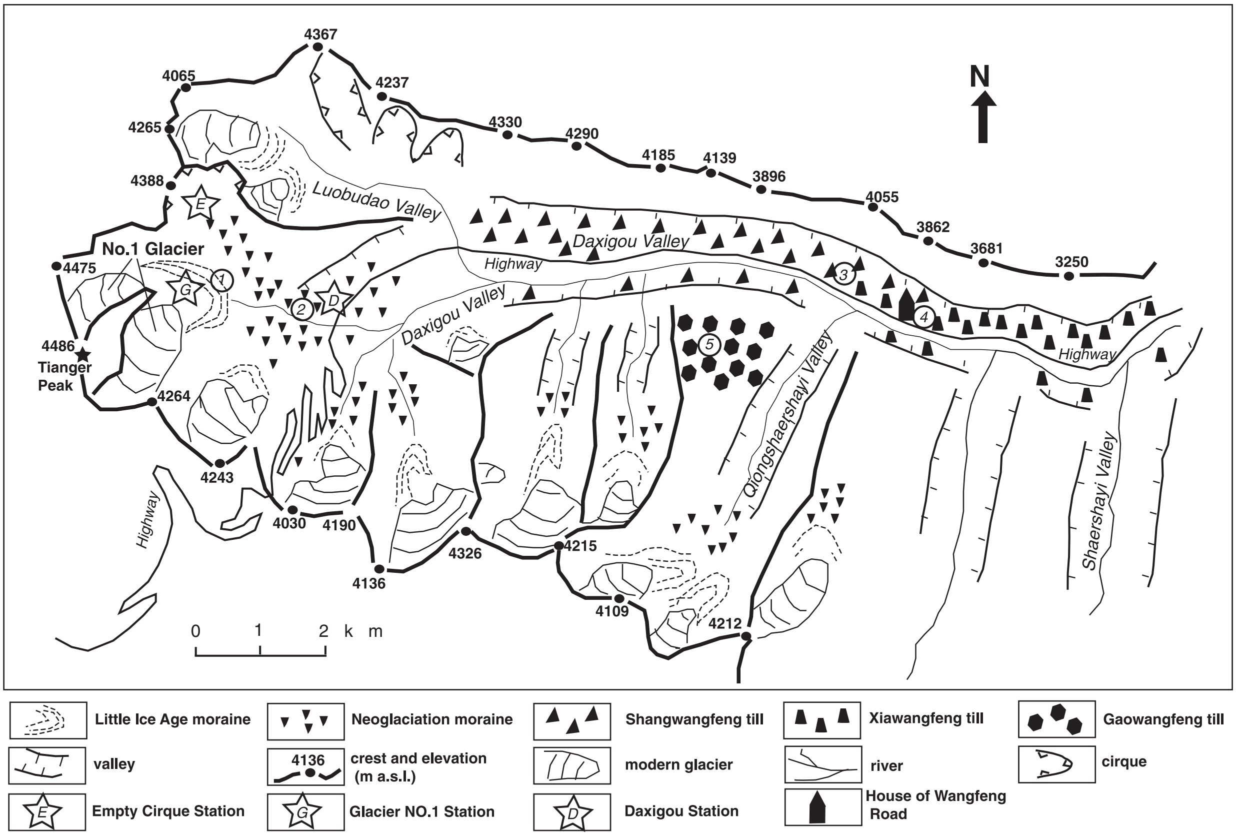

Fig. 2. Geomorphological map of Quaternary glaciation in the Urumqi River Valley, eastern Tianshan. The circles with different numbers indicate the sample sites: 1 the lichen and AMS ^{14}C samples from the LIA moraines; 2 the AMS ^{14}C and ^{14}C samples from the Neoglacial moraines; 3 the ESR, AMS ^{14}C and ^{14}C samples from the Shangwangfeng till; 4 the ESR samples from the Xiawangfeng till; and 5 the ESR samples from the Gaowangfeng till (see more in Table 1).

Glacial extent and timing of selected areas

Urumqi River Valley

The Urumqi River Valley is located on the northern slope of the eastern Tianshan in Xinjiang, China. Most ridges in this valley reach 4100–4300 m a.s.l., and the modern equilibrium-line altitude (ELA) is between 4000 and 4100 m a.s.l. (Qin *et al.* 1984; Yi *et al.* 2001). All of the glaciated area (35.7 km^2) is preserved within the Daxigou Valley, which serves as the main tributary of the Urumqi River. There are five sets of Quaternary glacial moraines along the Daxigou Valley extending ~19 km from the snout of the No. 1 Glacier to the Shaershayi Valley (Fig. 2). From youngest to oldest, these glacial stages are: Little Ice Age (LIA), Neoglacial, Shangwangfeng, Xiawangfeng and Gaowangfeng.

The LIA moraines are three arced end moraines at 250–550 m from the terminus of the No. 1 Glacier at an elevation of 3650–3690 m a.s.l. Based on the lichenometrical dating, these moraines formed at AD 1538±20, AD 1777±20 and AD 1871±20 (Chen 1989). The second set of moraines is present near the Glacier Observation Station and the Tianshan Weather Station, about 1500 m away from the end of the No. 1 Glacier and terminating at about 3500 m a.s.l. Radiocarbon (^{14}C) ages on those moraines are 6.49, 4.59 and 4.38 cal. kyr BP (Zheng & Zhang 1983); AMS ^{14}C ages are 1.79 (inner layer of carbonate coating) and 7.46 cal. kyr BP (outer layer of carbonate coating), indicating that they formed during the Neoglacial (Yi *et al.* 2004).

The Shangwangfeng and the Xiawangfeng moraines are distributed in the lower U-shaped valley (Fig. 3). The Shangwangfeng till originates at the Luobudao Valley outlet (~3550 m a.s.l.) and terminates around the House of the Wangfeng Road (3000 m a.s.l.), which is a highway maintenance station. Based on the landforms and one ^{14}C age of 17.89 cal. kyr BP on the Shangwangfeng moraines, Wang (1981) argued that the maximal glacial advance during this stage took place between ~18 and ~20 kyr BP (MIS 2). Utilizing the AMS ^{14}C methods, Yi *et al.* (2004) dated the Shangwangfeng moraines to 22.66 cal. kyr BP and 23.08±0.5 kyr BP. Using ESR methods, however, Yi *et al.* (2001) and Zhao *et al.* (2006) provided moraine ages of 37.4 and 35±3.5 kyr, respectively. The Xiawangfeng till, which extends downstream to the Shaershayi Valley (~2880 m a.s.l.), can be divided into an upper and a lower portion. The lower portion was

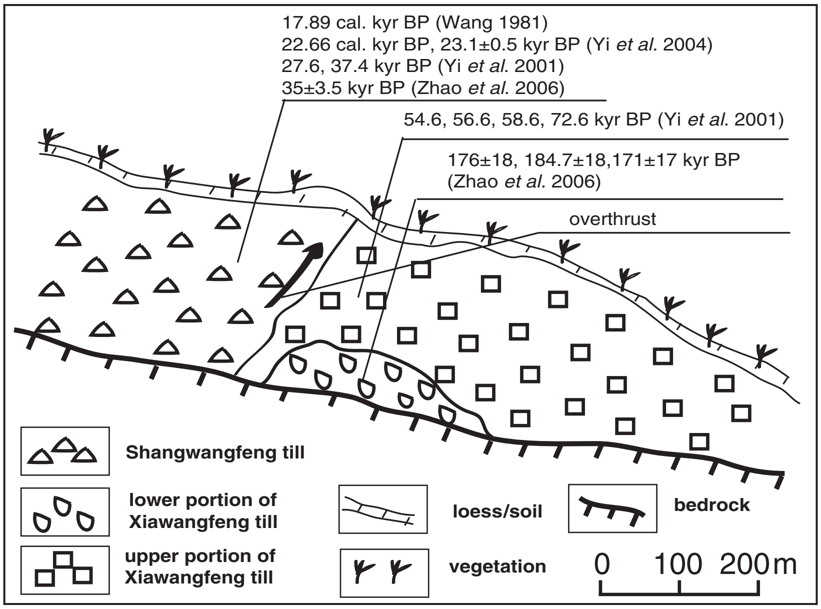

Fig. 3. Stratigraphical relationship between the Shangwangfeng and Xiawangfeng tills and their absolute ages.

destroyed, and only a section around the House of the Wangfeng Road was well preserved (Fig. 3). Li (1995) speculated that the Xiawangfeng till was formed in later parts of the Last Glacial based on TL dating of fluvial sand at the bottom of the till, but Yi *et al*. (2001) and Shi & Yao (2002) argued that it was deposited in MIS 4 and MIS 3 on the basis of ESR ages. Furthermore, Wang (1981) concluded that the till was formed in MIS 6 based on geomorphologic stratigraphy. To resolve this, Zhao *et al*. (2006) tested three ESR samples taken from the lower portion of the Xiawangfeng till and concluded that it was formed in MIS 6. Zhou *et al*. (2002) determined the ESR ages of the outwash terraces in this region, concluding that the second terrace formed in MIS 6, i.e. closely related to when the Xiawangfeng till formed. Noticing that the dated samples studied by Yi *et al*. (2001) were taken from the upper portion of the Xiawangfeng till, Zhao *et al*. (2006) concluded that the Xiawangfeng till was formed in two different glaciations – MIS 4 for the upper part and MIS 6 for the lower part.

The Gaowangfeng till was preserved in the upper valley, with the elevation of ~3450 m a.s.l., ~500 m above the modern river. The Gaowangfeng stage is the oldest in this area, with ESR ages of 477.1 and 459.7 kyr for its moraines (Zhou *et al*. 2001; Zhao *et al*. 2006).

Ateaoyinake River valley

The Ateaoyinake River originates from the southern slopes of Tumur Peak in central Tianshan and flows south into the Tarim Basin. Most mountain ridges above the valley are at altitudes of 4000–5000 m a.s.l., with the modern snowline at ~4500 m a.s.l. (Huang 1944; Feidaoluoweiqi & Yan 1959; Shi *et al*. 1984). There are 14 modern glaciers in the headwaters of the Ateaoyinake River, of which Keqicarbaxi and Yishetalage Glacier are the biggest (Lanzhou Institute of Glaciology and Geocryology 1985). Su *et al*. (1985) and Zheng (1985) recognized four or five sets of moraines based on geomorphological features, but they did not provide numerical ages. Zhao *et al*. (2009) identified seven sets of moraines extending 11 km from the end of Keqicarbaxi Glacier to piedmont (~2100 m a.s.l.) in this valley (Fig. 4), and dated them using ESR methods.

The first set, including 1–2 end moraines, occurs on either side of Keqicarbaxi Glacier rising 5–20 m above the ice. Dendrochronology on shrubs collected at ~3000 m a.s.l. provides a minimum age of 72–77 years, suggesting that the moraines formed during the LIA (Zhao *et al*. 2009).

The second set of moraines extends to two sites, one of which is within ~1 km of the end of Keqicarbaxi Glacier. Several end moraines extend down to 2990 m a.s.l., which indicates that the glacier was ~27 km in length at this glacial time. The other site is ~1.2 km away from the end of the modern Yishentalaga Glacier, where three end moraines stretch for ~1 km.For the former, three samples were dated using ESR methods, and gave ages of 6.8±0.6 (outwash sand), 3.4±0.3 and 7.3±0.8 kyr (outwash sand), indicating that the moraines formed during the Neoglacial (Zhao *et al*. 2009).

The third set of moraines is within 1–5 km of the terminus of Keqicarbaxi Glacier and within 5 km of Yishentalaga Glacier, terminating at an altitude of 2700–2990 m a.s.l. The Keqicarbaxi and Yishentalaga glaciers once coalesced and formed a large compound valley glacier that was 29 km long, with an area of ~12 km^2. Zhao *et al*. (2009) provided five ESR ages for these moraines (14.3±1.3, 18.1±1.8, 21.1±2.1, 17.4±

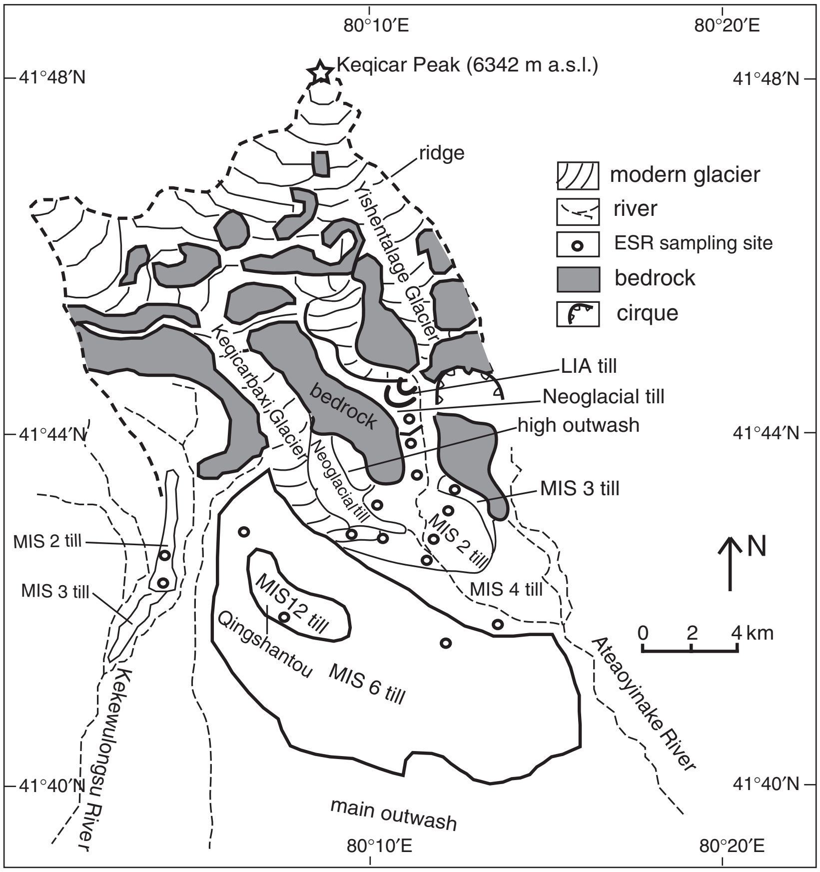

Fig. 4. Map of glacial landforms in the Ateaoyinake River Valley, central Tianshan (after Zhao *et al.* 2009).

1.6 and 26.7±2.5 kyr) showing that this set of moraines formed during MIS 2 and one age of 12.3±1.2 kyr that is consistent with the Younger Dryas Stage.

The fourth set of moraines, which largely underlies the third set, covers an area of about 13 km^2, with only ~1 km^2 exposed NE of the third set. The ages of four ESR samples tested on this set of moraines are 40.9±4.0, 46.2±4.2, 51.0±4.8 and 54.0±5.2 kyr.

The till of the fifth set occurs from 2700 to 2250 m a.s.l. It has an area of ~20 km^2, with several arced end moraines in the SE between 2500 and 2250 m a.s.l., indicating that the Keqicarbaxi Glacier was ~35 km long in this glaciation. This set of moraines was dated to 62.3±5.8, 55.4±5.2 and 60.2±5.7 kyr BP by ESR methods.

The sixth set of moraines presents on both sides of the Keqicarbaxi Glacier extending from an altitude of 3300 to 2100 m a.s.l. on the south side and from 3250 to 3040 m a.s.l. on the north. This set of moraines has an area of 40 km^2 and is the largest of the glacial successions, but it is lower in height (only 3–20 m) due to long-term weathering and mass movement. Zhao *et al.* (2009) tested two ESR samples for this set of moraines and provided the ages 134.4±12.6 and 219.7±20.5 kyr. The ages do not overlap and might not represent the same event, but they bracket the three ESR ages from the lower part of the Xiawangfeng till in the Urumqi River Valley. Zhao *et al.* (2009) concluded that this set of moraines was deposited during the Penultimate Glaciation (MIS 6).

A high and glaciated plateau (~3300 m a.s.l) known as 'Qingshantou' overlies the red Tertiary bedrock. Zhao *et al.* (2009) named it the 'Qingshantou glacial stage' and speculated that the Qingtoushan moraines were produced by an ice cap. One sample from the Qingshantou moraine dates the glaciation to 440.6± 41.7 kyr BP, which is consistent with the ESR ages from Gaowangfeng till in the Urumqi River Valley.

Terskey Ala Tau Range

The western part of the Tianshan is within the Kyrgyzstan Republic. In this region, the modern ELA lies within the altitude range 3700–3800 m a.s.l. in the north and 3900–4200 m a.s.l. in the south (Krenke 1982). Knowledge about the sizes and types of former glaciers is controversial, however, especially as to whether an ice cover occurred in the Tianshan during the Last Glacial. Some researchers have argued that, at the LGM, continuous ice covers buried the Tianshan ranges, and their outlet glaciers descended to the foothills, i.e. to 1500 m a.s.l. in the south and 900–1000 m a.s.l. in the north (Grosswald *et al.* 1994; Kuhle 1994; Kuhle

Fig. 5. Topographic map showing the studied sites in western Tianshan (adapted from online Google Map). This figure is available in colour at http://www.boreas.dk.

et al. 1997). The opposite view is that the glaciers had larger extents before the Last Glacial, and that no continuous large ice cover existed during the Last Glacial (e.g. Sevastianov 1991; Koppes *et al.* 2008). The ELA depression during the Last Glacial was estimated as only 200–1200 m, and geographically differentiated (Markov 1971; Maksimov 1980). These studies provided little if any detailed glacial chronologies. Recently, also Narama *et al.* (2007, 2009) and Koppes *et al.* (2008) investigated the glaciation in the western Tianshan by dating moraines. Here we focus on four ranges: Terskey Ala Tau Range, At Bashi Range, Kyrgyz Front Range and Torugrat Range (Fig. 5).

The Terskey Ala Tau Range extends along the south shore of the Issyk Kul Lake in NE Kyrgyzstan, with peaks and modern snowline being ~4100 m and ~3960 m a.s.l., respectively (Prokopova & Fateev 1974). For glacial extent and dating, Koppes *et al.* (2008) worked at two sites (Gulbel Pass in the eastern part of this range and Ala Bash basin in the western part), while Narama *et al.* (2009) studied the northern flank of the range.

The Late Quaternary moraines (Units 1–5) on Gulbel Pass extend from the snouts of modern glaciers to an altitude of 2620 m a.s.l. (Fig. 6A). The Unit 3 moraines extend over the largest area in the Korumdy Valley, and the glacier that formed this unit of moraines did not overtop the pass. Moraines of Units 4 and 5 are present not only east of Gulbel Pass, but also on the south slope of the Korumdy Valley above the Unit 3 moraines. Koppes *et al.* (2008) dated two boulders for each of the Unit 4 and 5 moraines (east of Gulbel Pass) and one sample (of Unit 4 or 5) from the Korumdy Valley using CNR methods (Table 1).

As regards the western part of the Terskey Ala Tau Range, Narama *et al.* (2007) and Koppes *et al.* (2008) identified four and five units of moraines, respectively (Units 1–5), in the Ala Bash Basin. The moraines in this basin extend to the piedmont at an altitude of ~2200 m a.s.l. (Fig. 6B). The Unit 1 and 2 moraines are located in six cirques, being 0.5–1.5 km away from the modern cirque glaciers. The Unit 3 moraines stretch over the largest area in Ala Bash basin, with the older moraines of Units 4 and 5 extending a short distance from beneath its end. Koppes *et al.* (2008) dated 13 samples using CNR methods and Narama *et al.* (2007, 2009) provided the OSL ages for the Last Glacial moraines (Table 1).

At Bashi Range

The At Bashi Range extends from west to east in the south of the Kyrgyzstan Republic with its spine separating the At Bashi (north) and Aksai (south) basins. Peak altitudes in this range reach 4200–4600 m a.s.l., with the modern glacial snowline being 4150–4040 m a.s.l. (Thompson *et al.* 2002). Koppes *et al.* (2008) studied the glacial moraines at two sites: the Terekcu Valley in Bashi Basin and the Djo Bog Gulsh Valley in the Aksai Basin. Narama *et al.* (2009) examined the Last Glacial moraines on the northern flank of this range.

In the Terekcu Valley, four units of moraines exist from the modern glacial terminal (~3730 m a.s.l.) to the piedmont at 2365 m a.s.l. (Fig. 7A). The Unit 1 moraines terminate at 3670 m a.s.l., where a set of lower moraines (Unit 2) extends beneath the Unit 1 to an altitude of 3525 m a.s.l. The end moraines of Unit 3 are simple and terminate on the upper piedmont at 2365 m a.s.l. The Unit 4 moraine has a limited extent and may represent a degraded piedmont complex. Koppes *et al.* (2008) tested only one sample for each of the Unit 3 and 4 moraines and gave the CNR ages that range from 31.6±2.4 to 33.5±2.7 kyr and from 52.5±4.0 to 58.0±5.0 kyr, respectively. The CNR age of Unit 3 is consistent with the OSL age (33.4±2.7 kyr) by Narama *et al.* (2009).

In the Djo Bog Gulsh Valley, a few modern glaciers remain in the upper valleys with steep slopes, and most

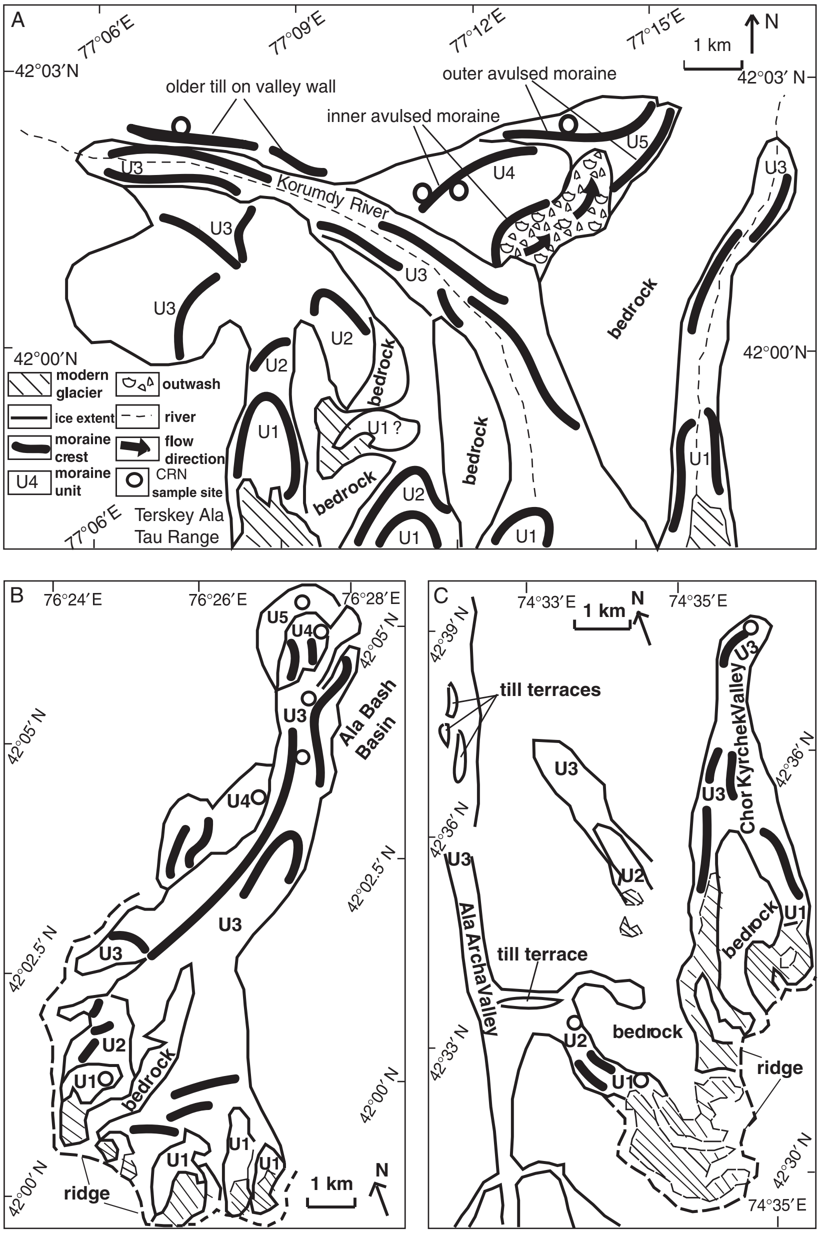

Fig. 6. Geomorphological map of Quaternary glaciation for (A) Gubel, (B) Ala Bash and (C) Ala Archa in western Tianshan. The legend in (A) is also used for (B), (C) and maps in Fig. 7 (modified after Koppes *et al.* 2008).

of the cirques are ice-free. Multiple ridges of the Unit 1 moraines lie below some of these cirques and terminate at ~3730 m a.s.l. (Fig. 7B). The Unit 2 moraines extend over the largest area and to the upper piedmont of the Aksai Basin. At least two older moraine sets (Units 3 and 4) protrude from beneath the Unit 2 moraines. One CNR exposure age for Unit 2 is 7.4±0.6 kyr, and two CNR ages for Unit 1 are 4.6±0.3 and 4.4±0.3 kyr. These are all minimal ages (see Table 1 for details). In addition, Narama *et al.* (2009) provided OSL ages for the Last Glacial moraines in the NE part of the At Bashi Ranges (Table 1). Their results imply that the glacier advanced during late MIS 3 and MIS 2 (31.5±2.7, 26.3±2.2, 24.3±1.9 and 17.9±1.4 kyr), but with a larger extent at late MIS 3.

Kyrgyz Front Range

The Kyrgyz Front Range lies in the north of the Kyrgyzstan Republic, NW of the Tianshan. The peak altitudes average ~4000 m a.s.l., and the modern ELA is ~3870 m a.s.l. Koppes *et al.* (2008) studied the extents and timing of glaciations in two valleys, the Ala Archa and the Chor Kyrchak.

The Ala Archa valley is on the north slope of this range, ~45 km south to the capital city, Bishkek. The valley was extensively glaciated down to an altitude of 1580 m a.s.l. during the Late Pleistocene (Fig. 6C). The only well-preserved moraines (Units 1 and 2) are in cirques within a few kilometres of the modern glaciers. The CNR ages for the Unit 1 and 2 moraines are 0.2 and

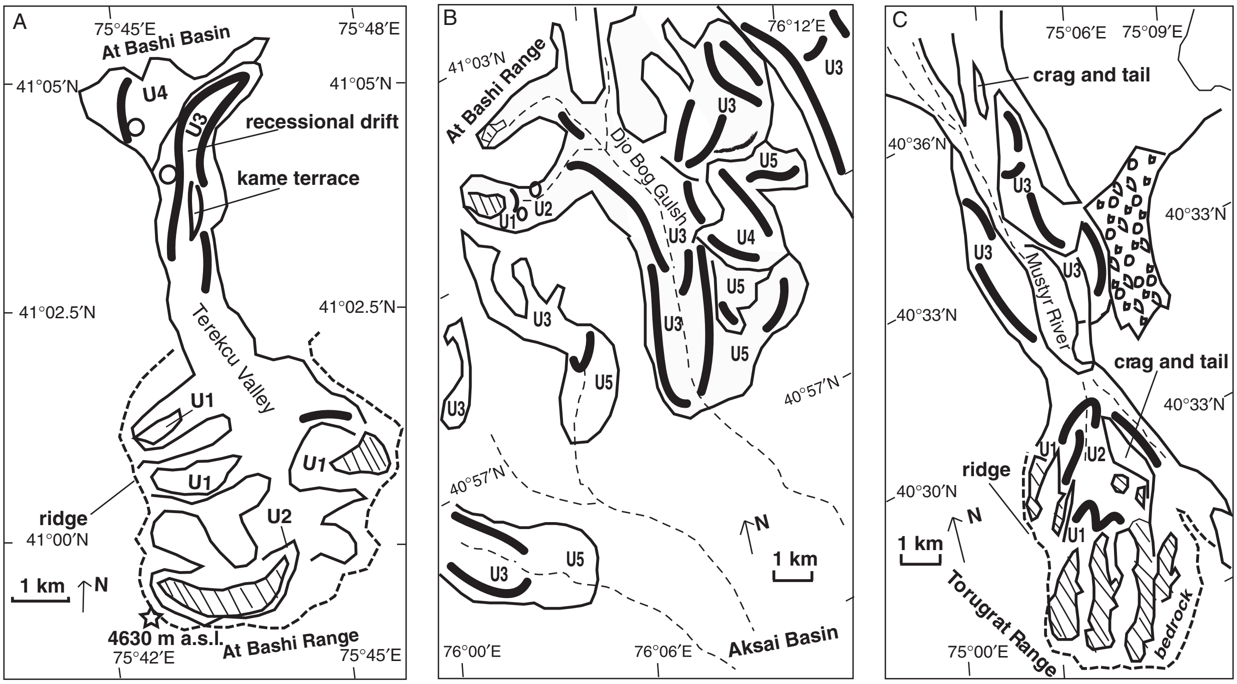

Fig. 7. Geomorphological map of Quaternary glaciation for (A) At Bashi, (B) Aksai, and (C) Mustyr in the western Tianshan (modified after Koppes *et al.* 2008).

0.5 kyr (Table 1). The neighbouring Chor Kyrchak valley was also extensively glaciated (Fig. 6C). Young moraines (Unit 1 or 2) and active glaciers are present upvalley, and an older set of moraines (Unit 3) extend down to an altitude of ~1500 m a.s.l. Koppes *et al.* (2008) provided only one CNR age of ~50 kyr for the Unit 3 moraines.

Torugrat Range

The Torugrat range is the southernmost high ridge of the western Tianshan and borders the southern end of the Aksai Basin. Peak altitudes average ~5000 m a.s.l., and the modern snowline rises to ~4340 m a.s.l. Modern glaciers are restricted in cirques and terminate at 4140 m a.s.l. in upper valleys of the Torugrat Range. The northern slopes were deeply incised and glaciated, while the southern slopes were not largely glaciated because of their steeper walls.

The Mustyr River valley is in the west of the range, with an average altitude of 3350 m a.s.l. In this valley, Koppes *et al.* (2008) identified three glacial advances (moraines of Units 1–3). In the upper Mustyr valley, moraines of Units 1 and 2 extend down to 3850 m and 3650 m a.s.l., respectively (Fig. 7C). The extensive Unit 3 moraines penetrate into the piedmont at an altitude of ~3550 m a.s.l. and appear to be composed of two separate ridges (Unit 3a and inner Unit 3b).

Palaeo-ELA reconstruction

The methods and problems associated with determining palaeo-ELA for mountain glaciers have been discussed in previous studies (Benn & Lehmkuhl 2000; Porter 2001; Benn *et al.* 2005; Osmaston 2005; Owen & Benn 2005). For the Urumqi River Valley, we adopted the Maximum Elevation of Lateral Moraine (MELM) method (Benn & Lehmkuhl 2000; Ju *et al.* 2004) and the Terminus-to-Headwall Altitude Ratio (THAR) method (Porter 2001; Benn *et al.* 2005) to estimate the palaeo-ELAs. The results and associated information are listed in Table 2.

Zhao *et al.* (2009) described the Quaternary glacier moraines preserved in the Ateaoyinake Valley (reviewed above), and adopted the THAR method to calculate the palaeo-ELAs for the central Tianshan (see Table 2). Because little information about the elevation of the highest lateral moraines is available to accurately adjust the THAR method in this region, our THAR-derived ELAs should be regarded as tentative values.

Koppes *et al.* (2008), also using the THAR method, calculated the palaeo-ELAs for the llgm for the western Tianshan. Where possible, they also measured the highest altitudes of llgm lateral moraines to compare with the THAR-derived values. We list these palaeo-ELA results in Table 2.

Discussion

Uncertainties related to the dating results

ESR dating is based on the assumption that the paramagnetic centre in quartz grain from sediment is bleached before the sediment is deposited. During

Table 2. Palaeo-ELA reconstruction for the Tianshan.

Range	Modern	Neoglacial			MIS 2			MIS 3			MIS 4		
	ELA	TA	ELA_T	ELA_M	TA	ELA_T	ELA_M	TA	ELA	ELA_M	TA	ELA_T	ELA_M
Eastern Tianshan													
Urumqi River Valley	4050	3500	3940	3630	3000	3690	3550		Lower than MIS 2		2880	3630	–
Central Tianshan													
Ateaoyinake River Valley	4500	2990	4470	–	2700	4325	–		Lower than MIS 2		2250	4100	–

Western Tianshan		Local last glacial maximum		
Terskey Ala Tau	3890	TA	ELA_T	ELA_M
Gulbel		2620	3180	–
Ala Bash		2200	2950	–
Kyrgyz Front Range	4010	TA	ELA_T	ELA_M
Chor		2040	2450	–
At Bashi Range	4090	TA	ELA_T	ELA_M
At Bashi		2415	2960	–
Aksai		3380	3750	3580
Torugart Range	4230	TA	ELA_T	ELA_M
Mustyr		3450	3931	3890

TA = terminal moraine altitude (m a.s.l.).
ELA_T = ELA calculated by the THAR method (m a.s.l., THAR = 0.5 for eastern and central Tianshan; THAR = 0.4 for western Tianshan).
ELA_M = ELA derived from the MELM method (m a.s.l.).

glacier movement, sediment grinding is a reasonable mechanism bleaching the ESR signal (cf. Buhay *et al.* 1988; Yi 1997; Ye *et al.* 1998). Zhao *et al.* (2009) argued that during determination of U and Th concentrations, and of K_2O content for the calculation of environmental dose rate (De), the measurement error can contribute an uncertainty of 5%–10% on the dating results, and that water content reduces the dose rate with an uncertainty of 5%. Unfortunately, Yi *et al.* (2001) did not assign or discuss any uncertainties in their ESR dating results, which makes it difficult to access the validity of their results and to compare them with other dating results.

The OSL signal is sensitive to light, so sunlight is likely to completely bleach the OSL signal of sediment when glacial deposits are exposed to it (Richards 2000; Fuchs & Owen 2008). In measuring the OSL signal from individual grains and calculating the equivalent dose (D_e), researchers can now estimate whether a significant proportion of the quartz grains in a sediment unit was likely to have had the fast component of the OSL zeroed by sunlight exposure at deposition (Duller 2008; Wintle 2008). However, because of large numbers of the grains in each aliquot, it is difficult to assess whether a sample is well bleached or not from analysing the distribution of D_e values, especially using fine grains. To resolve this, Narama *et al.* (2009) compared their ages obtained from moraines of same glaciations at different valleys and then checked whether they were consistent; eventually they gave the dating error in terms of 1 SD ($\pm 1\sigma$).

Previous researchers have discussed the problems relating to the application of CNR methods to dating moraines (Hallet & Putkonen 1994; Owen *et al.* 2002, 2005, 2009; Owen 2008; Seong *et al.* 2009). Owen (2008) and Owen *et al.* (2009) concluded that two sets of factors hinder the ability of CNR methods to define glacier ages. One relates to geological aspects, such as weathering, exhumation, prior exposure and shielding of the surface by sediment and/or snow, i.e. aspects that cause the true age of the landforms to be underestimated or overestimated. These factors could be assessed by testing multiple samples on one moraine, and the geological factors could contribute an uncertainty of more than 20% of a true CNR age (Putkonen & Swanson 2003; Owen 2008). The other set of factors is in calculation of the CRN production rate, because this has varied spatially and temporally in association with variations of the geomagnetic intensity and atmospheric pressure throughout the Quaternary. Currently, there is much debate regarding the appropriate scaling models and geomagnetic corrections for CRN production in calculating CNR ages (Pigati & Lifton 2004; Owen. 2008). However, Owen (2009) has emphasized that the true uncertainty in the CNR ages between scaling models may be as much as 20% by analysing the error effects of four different scaling models on the Mount Everest area. It is reasonable to conclude that, in the Tianshan, the geological and scaling model uncertainties are smaller than those in the Mount Everest area, because the Tianshan lies at relatively high latitude and has lower altitudes.

The CNR samples of Koppes *et al.* (2008) were taken from the boulder tops on moraine crests. The boulders were sampled > 1 m above the moraine surfaces in order to reduce the possibility of burial/exhumation histories and shielding by sediment and/or snow. Assuming no prior exposure, calculating their CNR ages could result in an overestimate of the true ages; Putkonen & Swanson (2003), however, showed that only ~2% of all dated boulders had had prior exposure. The uncertainties of each CNR age are 1 SD (±1σ, 68% confidence) including ^{10}Be concentration measurement uncertainties and an assumed uncertainty of ±6% in ^{10}Be production rate scaling. However, a problem with the moraine ages of Koppes *et al.* (2008) is that only 1–4 samples on each moraine were tested, so it is difficult to assess the uncertainty caused by the geological factors effectively. Their dating results can only be used as tentative evidence to infer the Tianshan glaciations.

Synthesis of glaciations in the Tianshan

It can be concluded from the present knowledge of glacial extent and timing in the Tianshan that at least five glaciations once occurred in this region during the late Quaternary. Although only three to four units of moraines were identified at the At Bashi, Kyrgyz Front and Torugart ranges, two older moraines might have been less extensive and buried by subsequent moraines of Unit 3 (Koppes *et al.* 2008). Based on the current dating evidence, the oscillations of the Tianshan glaciers were broadly synchronous during MIS 6, 4, 3, 2 and the middle to late Holocene, but with an exception of glacial advance during MIS 5 in the western part. In addition, an older glacial advance during MIS 12 was identified in eastern and central Tianshan with ESR ages of 440.6±41.7 kyr in the Ateaoyinake River Valley and of 459.7±46 and 471.1 kyr in the Urumqi Valley (Zhou *et al.* 2001; Zhao *et al.* 2006). Given the uncertainty of dating methods, these glacier fluctuations were probably synchronous with the dynamics of the Northern Hemisphere ice sheets (Svendsen *et al.* 2004) and with the variations of δ^{18}O records from the Greenland ice cores (Dansgaard *et al.* 1993) (Fig. 8), especially manifested in MIS 6, 4 and 2. However, the glacial extent and timing shows a trend of major glacial advances during the Late Quaternary becoming progressively less extensive with time in the eastern and central regions. The palaeo-ELA in eastern and central Tianshan had an increasing tendency from MIS 4 to the present, and the ELA depression was about 420 m during MIS 4 (Table 2).

The glacial succession in the western part is more complicated. In the eastern part of western Tianshan (Terskey Ala Tau Range), the glacial succession is similar to that in central and eastern Tianshan, but in northern and southern parts (At Bashi Range, Kyrgyz Front Range and Torugart Range) the llgm glaciers probably eroded and partly buried the older moraines. However, the presence of moraines that pre-dated the Last Glacial is strong evidence that an extensive ice cover, as proposed by Grosswald *et al.* (1994), Kuhle (1994), Kuhle *et al.* (1997), could not have existed in western Tianshan during the Last Glacial. Had such an ice cover developed, the glacial landforms from earlier glaciations would have been eroded away or poorly preserved, and thus could not have been dated pre-MIS 2. In contrast, during the MIS 2 the glacial extent was more restricted in western Tianshan than in the eastern and central regions. Finally, we note that during the Holocene there were probably more glacial advances in eastern and central Tianshan than in the western region, which can be seen from the Holocene moraine series in those different parts.

The source of moisture

The source of moisture in the Tianshan has been related to two climatic systems: the mid-latitudinal westerly and the Asian monsoon (Yang *et al.* 2004). When the westerly wind arrives in Central Asia, and thereby the Tianshan, the moisture content decreases due to distance from the oceans and has a decreasing trend from western Tianshan to eastern Tianshan. In addition, summer precipitation is a key factor for the glacier fluctuations in the Tianshan, suggesting that summer is not just the ablation season but also the accumulation season for glacial mass balance (Shi 2002). If ascribed only to the contribution of westerly wind, the western Tianshan should receive more precipitation and thus be more favourable for glacier advance than eastern and central Tianshan. However, based on the glacial extents, this is not the case, especially in MIS 2 and the Holocene (Neoglacial and LIA), when the glaciers advanced more extensively and frequently in eastern and central Tianshan. During the llgm, the ELA descended to 2450–3931 m a.s.l. in western Tianshan and to 3630–4100 m a.s.l. in the eastern and central regions (Table 2). This suggests that during the early parts of the Last Glacial (MIS 4/MIS 3) the Tianshan was predominated by the mid-latitude westerly that brought more moisture to western Tianshan than to eastern and central Tianshan. However, during MIS 2 and the Holocene, the ELA lowering was greater in eastern and central Tianshan than in the western region, suggesting that the Asian monsoon likely influenced eastern and central Tianshan during this time. Moisture from the Indian Monsoon cannot reach Tianshan because of the Himalaya Mountains and the Tibetan Plateau blocking the airflow (Qin *et al.* 1984; Benn & Owen 1998). In contrast, the SE Asian Monsoon, which can readily shift northwestwards, could penetrate into eastern Tianshan at least in MIS 2 and the Holocene. Also, on analysing

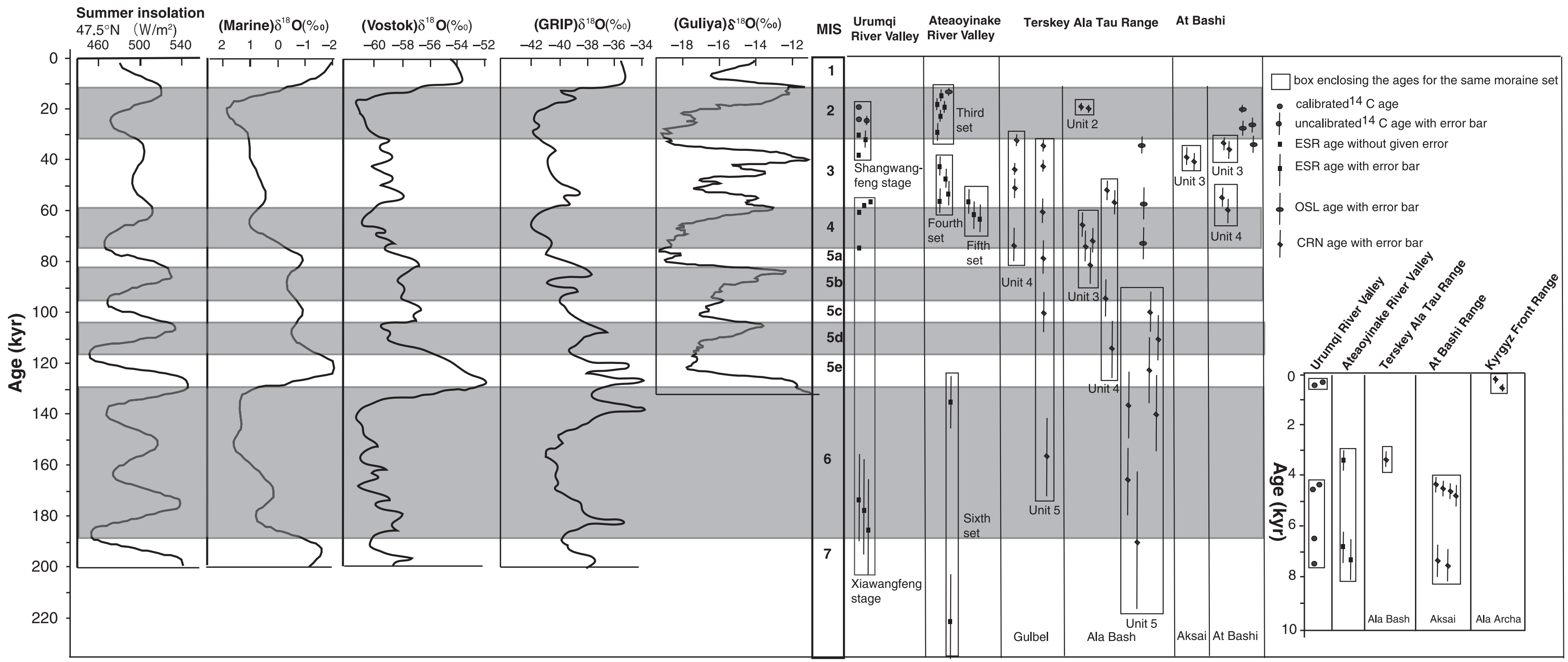

Fig. 8. Comparison of the glaciation chronology for Tianshan with summer insolation value (Berger & Loutre 1991), major climatic changes recorded in deep-sea core (after Imbrie *et al*. 1984), Vostok ice core (Antarctica) (Jouzel 1994), GRIP ice core (Greenland) (Dansgaard *et al*. 1993) and Guliya ice core (northwestern China) (Yao *et al*. 2000). The grey bands show MIS durations derived from deep-sea core (Imbrie *et al*. 1984).

lake sediments close to or in the Tianshan (Boston Lake, Xinjiang (Wunnemann *et al.* 2006; Mischke & Wunnemann 2006) and Issyk Kul Lake, Kyrgyzstan (Tarasov & Harrison 1998; Ricketts *et al.* 2001)), researchers have argued that these lake levels were much higher in the middle Holocene (~6 kyr BP), attributing this to more moisture from the maximum expansion of the Asian monsoon.

Lack of synchronicity of glacial advances

In recent years, increasing evidence has confirmed Gillespie & Molnar's (1995) view that the maximum advances of glaciers were not synchronous throughout the world, not even in Asia (Philips *et al.* 2000; Shi 2002; Cui & Zhang 2003; Owen *et al.* 2003a, b; 2006; Owen 2008). Here, it is necessary to distinguish between the llgm and the LGM because these probably do not refer to the same glacial periods, especially in the case of the mountain glaciations in High Asia. Gillespie & Molnar (1995) stressed that glaciers in many mountain regions may have reached their maximum extent during the early parts of the Last Glacial. Strictly speaking, these glacial advances and the landforms they produced should be informally assigned to the llgm until they have been dated and shown to be LGM in age (Owen 2008). Owen *et al.* (2002) found that the largest glacial extent in southern Tibet during the Last Glacial stage occurred in MIS 3 (40–56 kyr BP) and did not coincide with the LGM found in the Vostok ice core in Antarctica, the GRIP ice core in Greenland, and the marine oxygen isotope record (Fig. 8). Moreover, Benn & Owen (1998), in evaluating the glacial extent and timing of many specific areas on the Tibetan Plateau, inferred that glaciations may have been asynchronous between different regions of the Tibetan Plateau.

In the Tianshan, this feature of the glaciation is evidence not just of Gillespie & Molnar's (1995) view, but also of its particular aspects. In the three parts of the Tianshan, the llgm evidently pre-dated the MIS 2, during which the Northern Hemisphere ice sheets reached their maximum. Moreover, on the Tibetan Plateau, the llgm occurred during the early part of the Last Glacial and in most areas during MIS 3 (Owen *et al.* 2002). A similarity can be also recognized in the Tianshan, where the llgm appeared during MIS 4 in the eastern and central parts and MIS 3 in the western part. Until now, little evidence concerning the alpine glacial advance during the MIS 5 has been reported on the Tibetan Plateau, potentially due to lack of suitable dating material or absence of glacial relicts probably destroyed by subsequent glacial advances or fluvial reworking. In the western Tianshan (Terskey Ala Tau Range), the glaciers also advanced during the MIS 5, suggesting that the glacial fluctuation during MIS 5 is also asynchronous between the Tianshan and the Northern Hemisphere ice sheets. Further studies are needed to confirm whether similar glacial advances during MIS 5 occurred at other sites in Central Asia.

Palaeoclimatic implications of glacial fluctuations

Glacial fluctuations in the Tianshan can be related to three climatic systems: westerly circulation, the Siberian High and the Asian monsoon. In interglacial times, when solar insolation was relatively high (Berger 1978), the ocean surface received more heat and thus increased the evaporation conducive to moisture transmission. The westerly wind could have brought more moisture to the Central Asian continent during these times (Yang *et al.* 2004). However, in glacial times, the Northern Hemisphere ice sheets advanced on a large scale, which could have intensified the Siberian High and forced it to shift southwards. This could mean that the Siberian High controlled the cooling temperature in Central Asia during glaciation. Moreover, during the glacial periods, moisture from the oceans was transferred to the worldwide ice sheets and resulted in a drawdown of global sea level (~100 m lower than present) (Qin *et al.* 1984), such that the moisture available for alpine glacial mass balance was limited. Based on this, the Late Pleistocene climate of the Tianshan had a background of cold–dry in glacial periods and warm–wet in interglacial periods. Zheng *et al.* (2002) studied the relationship between climate change and Quaternary glacial cycles on the Tibetan Plateau, and their results support this climatic alternation.

The glacials and interglacials, however, had their particular characteristics in the Tianshan. From $\delta^{18}O$ record of the Guliya ice core in NW China (Fig. 8), the decreasing amplitudes of temperature were similar during the glacial periods (MIS 6, 4 and 2), but the glacial extents were progressively less in the entire Tianshan. This suggests that the Late Pleistocene climate had an arid trend between the glacial periods, especially in eastern and central Tianshan. In addition, during MIS 2 the glacial extent was more extensive in eastern and central Tianshan than in the western part, indicating that the Siberian High and the weakening Asian monsoon probably affected eastern and central Tianshan during this time, and even to the Neoglacial and LIA of the Holocene (see above). However, during the interglacial periods (MIS 3, 5), the glacial advance in eastern and central Tianshan was less extensive than in the western part because the climate was more humid in the western part than in the eastern and central parts at this time. This discrepancy means that the westerly circulation was dominant in the Tianshan during the interglacial and thus brought more moisture to western Tianshan than to eastern and central parts.

Palaeoclimatic studies of other records have obtained similar results for the cold–dry and warm–wet climatic patterns in the Tianshan. Relatively warm–wet conditions during MIS 3 were also inferred from the Guliya ice core (Thompson *et al.* 1997; Yao *et al.* 1997, 2000), loess-palaeosol sequences on the Loess Plateau (Kukla & An 1989) and pollen records in Ladakh (Bhattacharyya 1989). Yang *et al.* (2004) reviewed the lake records close to or in the Tianshan and concluded that a warm and humid climate between 40 and 30 kyr BP occurred in this area. Based on the records from Ayding Lake in the south and Manas Lake in the north, researchers (Li *et al.* 1989; Rhodes *et al.* 1996; Thomas *et al.* 1996) found that the two lakes experienced a warm-humid period during MIS 5 (Ayding Lake) and MIS 3, and a cold–dry period during MIS 2. Ricketts *et al.* (2001) suggested that during MIS 2 less precipitation fell into the Issyk Kul basin in western Tianshan due to a dry air mass associated with the Siberian High. Moreover, grain-size variations of loess deposits in Central Asia indicate that the Siberian High was most pronounced during MIS 2 throughout the Last Glacial and more moderate during the late-MIS 4 and MIS 3 (Wu *et al.* 2006). Yi *et al.* (2008) compiled 53 radiocarbon ages for Holocene glaciations and identified corresponding glacial advances in the Tibetan Plateau and its surrounding mountains. They suggested that the Holocene glacial advances occurred at 9.4–8.8, 3.5–1.4 and 1.0–0.13 cal. kyr BP. However, in Tianshan, no glacial advance has been found in the early Holocene, which suggests that the region probably experienced a warm period during this time. For the Neoglacial, the glaciers prominently advanced in the eastern and central Tianshan during 7.0–4.0 kyr BP, but restrictedly expanded in the western Tianshan at ~3.0 kyr BP. The timing of LIA glacial advances in the Tianshan supports the view of Yi *et al.* (2008).

Conclusions

The Tianshan was extensively and repeatedly glaciated during the late Quaternary. Notable glacial advances occurred during MIS 6, 4, 3, 2, the Neoglacial and the LIA in the Tianshan and especially during MIS 5 in the western part. However, during MIS 6, 4, 2 and the Holocene, glaciers advanced more extensively in eastern and central Tianshan than in the western part, while during MIS 5 and MIS 3 the situation was the reverse. Furthermore, the llgm pre-dated the LGM during MIS 4 in the eastern and central parts and MIS 3 in the western part. These events suggest that local glaciations were out of phase not only with the Northern Hemisphere ice sheets, but also between different parts of the Tianshan. Glaciers in the Tianshan appear to respond primarily to changes in precipitation rather than to reduced regional temperatures, as indicated by the small size of the MIS 2 glaciers across the entire mountain range and larger extent during warmer MIS 3 and even MIS 5 (in western Tianshan), the periods of high summer insolation and minor global cooling.

The late Quaternary climate in the Tianshan had a background of cold–dry during glacial periods and warm–humid during interglacial periods. Specifically, the Late Pleistocene climate had an arid trend between the glacial periods in eastern and central Tianshan. Interpretation of such palaeoclimatic conditions is based on the influences of three climatic systems: the mid-high latitudinal westerly circulation, the Siberian High and the weakening Asian monsoon. During interglacial times, the westerly wind dominated the Tianshan, but during glacial times the Siberian High controlled the entire mountain area, and the southeastern Asian monsoon probably influenced the eastern and central regions of the Tianshan.

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